NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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COMPRESSIVE STRENGTH OF FLAT PANELS
WITH Z- AND HAT-SECTION STIFFENERS

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NACA

WASHINGTON

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ADVANCE RESTRICTED REPORT

COMPRESSIVE STRENGTH OF FLAT PANELS WITH Z- AND HAT-SECTION STIFFENERS

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SUMMARY

Compression tests were made of 247 panels with Z-section stiffeners and 304 panels with hat-section stiffeners. The specimens were constructed from artificially aged Alclad 24S aluminum alloy with minimum guaranteed yield strengths of 64 and 57 ksi for the stiffener and sheet materials, respectively.

Results of the tests are presented in charts that show the average stresses at the load for buckling of the sheet and at the maximum load. These average stresses have been adjusted to minimum guaranteed properties of the materials.

INTRODUCTION

In order to provide information on the compressive strength of stiffened panels with proportions varying over an extensive range, 247 panels with Z-section stiffeners and 304 panels with hat-section stiffeners were tested. The specimens were furnished by the Consolidated Vultee Aircraft Corporation.

The height, thickness, and spacing of the stiffeners; the thickness of the sheet; and the length of the specimens were varied systematically to show the effects of changes in these dimensions on the strength of the panels.

TEST SPECIMENS

Cross sections of the specimens tested are shown in figures 1 and 2. The four stiffeners were attached to

the flat sheet at three equal spacings. The width of sheet b_s for panels with Z-section stiffeners or the width of sheet b_2 for panels with hat-section stiffeners (see figs. 1 and 2) is referred to as "a bay."

The manufacturer furnished the following information regarding the specimens:

> The test specimens were made of artificially aged Alclad 24S aluminum alloy. The thickness of cladding on each side of the sheet was 5 percent of the over-all thickness. The grain in the material of the stiffeners and the sheet was parallel to the direction of the stiffeners.
>
> The stiffeners were formed to the desired shape by passing Alclad 24S-0 aluminum-alloy strip through a series of rolls. The formed stiffeners were heat-treated at 930° F from 30 to 45 minutes and then quenched. They were stretched to $3\frac{1}{2} \pm \frac{1}{4}$ percent permanent set immediately after quenching and were aged at room temperature for at least 96 hours. Alclad 24S-T sheet in the as-received condition was riveted to the stiffeners with 100° countersunk-head rivets. The assembled panel was artificially aged at 355° F for $9\frac{1}{4}$ hours and then cooled in air.

The cross-sectional area of each specimen was determined from the density of the material and the weight and length of each specimen, with proper allowance for the weight of the rivet heads.

The dimensions of the test specimens are designated by the symbols shown in figures 1 and 2, and the nominal dimensions are given in the charts that present the test results. In the preparation of the test data actual values of the dimensions, obtained by measurement of the specimens, were used.

METHOD OF TESTING

The specimens were tested, as shown in figures 3 and 4, in the 1,200,000-pound-capacity testing machine

in the NACA structures research laboratory. The load indicated by this testing machine is within plus or minus one-half of 1 percent of the true load. The loading head is laterally supported by the heavy side columns of the machine so as not to affect the accuracy of the load measurement.

The ends of each specimen were ground flat, parallel to each other, and square with the longitudinal axis of the specimen. The upper and lower guide bars shown in figure 3 were used to aline the ends of the specimens in order that they would remain flat and parallel in the testing machine. These guide bars were backed away from the specimen before the maximum load was reached.

Strains in the sheet and in the stiffeners were measured by Tuckerman optical strain gages of 1-inch and 2-inch gage lengths or by wire resistance-type strain gages of 1-inch gage length. From 6 to 23 gages were attached at approximately the midlength of the specimen. In addition, the shortening of each specimen was measured by dial indicators.

RESULTS

The average stress at maximum load was determined for each panel. This stress was adjusted to apply to a panel with equal numbers of stiffeners and bays and with the minimum guaranteed properties of the stiffener and plate materials. The procedures by which these adjustments were performed are described in the appendix.

Figures 5 to 12, parts (a), show for each panel the adjusted average stress at maximum load. For panels of the same cross section but of different lengths, curves are drawn through the test points or through points obtained by cross-plotting from parts (b) of figures 5 to 12. The strengths shown were obtained in flat-end tests in which the average coefficient of end fixity was 3.75. (See appendix.) As the aircraft designer is more frequently interested in the strength of sheet-stiffener combinations considered as columns with end-fixity coefficients of $c = 1$ or $c = 1.5$, the actual lengths of the test specimens have been reduced to equivalent lengths corresponding to these two values of end-fixity coefficient. The two abscissa scales on the charts

therefore show the lengths of sheet-stiffener combinations with end-fixity coefficients of $c = 1$ and $c = 1.5$ and with strengths equal to those of the test specimens.

If the charts of figures 5 to 12 are used for values of the end-fixity coefficient other than $c = 1$ or $c = 1.5$, the appropriate value of c is used to compute $L/\sqrt{c}$. With this value of $L/\sqrt{c}$, the strength of the panels can be determined from the charts.

The average stress in each panel when sheet buckling occurred is plotted in figures 13 and 14. The lower curve shows the theoretical buckling stresses for plates with side edges simply supported, and the upper curve shows the theoretical buckling stresses for plates with side edges completely restrained against rotation. These two curves are drawn for a modulus of elasticity of 9.75×10^6 psi and do not include a correction for a lower effective modulus at the higher stresses.

In figures 13 and 14, some of the test points lie above the theoretical curve for buckling of plates with side edges completely restrained. The principal reasons are believed to be: (1) the dimension b_s, b_1, or b_2, measured between center lines of rivet rows, was used in the plate-buckling formula to determine the theoretical curve, whereas the actual width of sheet that acts as a plate is somewhat less than b_s, b_1, or b_2 because some of the sheet is clamped between the rivet head and the attachment flange of the stiffener (2) the average strain for the sheet at the buckling load may be lower than the average strain for the panel. This condition of nonuniform strain may occur in some panels because, in finishing the ends of the panels, the grinding wheel tends to undercut the sheet between stiffeners, particularly when the sheet is thin compared with the material in the stiffeners.

The average stress at which buckling of the sheet occurred was determined by the method described in the appendix. On some specimens, buckling stresses were not obtained because strain gages could not conveniently be attached to both sides of the sheet, because the sheet buckled at loads so low that consistent strain readings could not be obtained, or because the sheet buckled near or at the maximum load. Buckling stresses for specimens of the same cross section but of different lengths were averaged and this averaged stress is indicated in parts (a) of figures 5 to 12 by a short horizontal line.

These buckling stresses are included for the use of the design engineer in determining the percentage of average stress at maximum load that a given sheet-stiffener combination will attain without appreciable buckling of the sheet.

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APPENDIX

PREPARATION OF DATA FOR PRESENTATION

The test data included measurements of shortening of the panel and of strain in the sheet and stiffeners for each panel at a number of loads varying from an initial load to a load near maximum.

The symbols used in the equations and figures for preparation and presentation of the test results are defined as follows:

a	distance from center line of outer row of rivets to edge of sheet, in.
b_s	stiffener spacing, in.
b_1, b_2	distance between center lines of adjacent rivet rows for hat-section stiffened panels, in. (See figs. 1 and 2.)
b_w	stiffener depth, in.
c	end-fixity coefficient in Euler column formula
d	rivet diameter, in.
p	rivet pitch, in.
t_s	thickness of sheet, in.
w_s, w_1, w_2	effective width of sheet corresponding to b_s, b_1, b_2, respectively, in.
A	total cross-sectional area of test specimen, sq in.
A_{st}	cross-sectional area of one stiffener, sq in.
F_{YP}	weighted compressive yield strength for a panel with equal numbers of stiffeners and bays, ksi
$(F_{YP})_s$	compressive yield strength for sheet material, ksi
$(F_{YP})_{st}$	compressive yield strength for stiffener material, ksi

L	specimen length, in.
P	maximum load on panel, kips
σ'	adjusted average stress at maximum load for a panel with an equal number of stiffeners and bays, ksi
σ_{cr}	stress in the sheet near stiffener when sheet buckling occurs, ksi
σ_s	stress in the sheet adjacent to stiffener at maximum load, ksi
σ_{st}	stress in stiffener at maximum load, ksi

The essential steps in preparing the test data for presentation were as follows:

(1) The load on the specimen was plotted against the shortening per inch of specimen length, and the strain at maximum load was obtained by extrapolation of the curve drawn in this plot. The strain was converted to stress in the stiffener σ_{st} by use of the stress-strain curve for the stiffener material.

(2) At maximum load, the longitudinal strain in the sheet near the stiffeners was assumed to be the same as the longitudinal strain in the stiffeners. This strain was converted to stress in the sheet σ_s from the stress-strain curve for the sheet material.

(3) The average stress at maximum load in panels with four Z- or hat-section stiffeners and three bays of sheet was in most cases adjusted to the stress in a panel with four stiffeners and four bays. For some panels with hat-section stiffeners, however, adjustment to a panel with three stiffeners and three bays was considered more accurate.

For the Z-section stiffened panels, the effective width of sheet acting with a stiffener at the maximum load was obtained from the equation

$$P = 4A_{st}\sigma_{st} + 3w_s t_s \sigma_s + 2at_s\sigma_s$$

or

$$w_s = \frac{P - 4A_{st}\sigma_{st} - 2at_s\sigma_s}{3t_s\sigma_s}$$

For hat-stiffened panels, it was necessary to determine the effective width of sheet between rivet lines of a stiffener as well as between adjacent stiffeners. Because there were two values of effective width of sheet for panels with hat-section stiffeners, the direct computation method, as used for the Z-stiffened specimens, could not be applied. A curve for w_s/b_s against σ_{cr}/σ_s was therefore constructed for the Z-stiffened panels. This curve was used to determine the effective widths of the sheet for the hat-stiffened panels at maximum load.

The foregoing procedure of applying the curve for Z-stiffened panels to hat-stiffened panels is considered permissible because the ratio of effective width to actual width as a function of the ratio of the critical stress to the edge stress in the plate is only slightly dependent on the restraint supplied by the stiffener to the sheet. This can be seen by plotting such curves from the theoretical results of Levy and Krupen for plates with simply supported and with clamped edges (reference 1).

(4) Adjustment of the average stress at maximum load for the test specimen to the average stress at maximum load for a panel with equal numbers of stiffeners and bays was performed by adjustment of the maximum load and the total area of the specimen. For the adjustment to a Z-stiffened panel with four stiffeners and four bays, the load was increased by the amount $\left(w_s - 2a\right)t_s\sigma_s$ and the area by $\left(b_s - 2a\right)t_s$. For hat-stiffened panels, a similar adjustment was made by increasing the load by $\left(w_2 - 2a\right)t_s\sigma_s$ and the area by $\left(b_2 - 2a\right)t_s$. The adjusted average stresses are given by the following equations: For Z-stiffened panels,

$$\sigma' = \frac{P + \left(w_s - 2a\right)\sigma_s t_s}{A + \left(b_s - 2a\right)t_s}$$

For hat-stiffened panels,

$$\sigma' = \frac{P + (w_2 - 2a)\sigma_s t_s}{A + (b_2 - 2a)t_s}$$

For the hat-stiffened panels in which the average stress at maximum load was adjusted to that of a panel with three stiffeners and three bays, the load was decreased by the amount equal to that carried by one stiffener $A_{st}\sigma_{st}$, by the sheet between rivet rows of a stiffener $w_1\sigma_s t_s$, and by the sheet beyond the outer rows of rivets $2at_s\sigma_s$. The cross-sectional area was decreased by the area of one stiffener A_{st} and by the area of sheet $(b_1 + 2a)t_s$. The adjusted average stress is given by

$$\sigma' = \frac{P - \left[A_{st}\sigma_{st} + (w_1 + 2a)\sigma_s t_s\right]}{A - \left[A_{st} + (b_1 + 2a)t_s\right]}$$

(5) The adjusted average stresses of step (4) were further adjusted to minimum guaranteed material properties by the method described in reference 2. Because the sheet and stiffener materials possessed different properties, it was necessary to determine a weighted yield strength for a panel. The weighted compression yield strength used for the panels of this investigation is given by

$$F_{YP} = \frac{A_{st}(F_{YP})_{st} + b_s t_s (F_{YP})_s}{A_{st} + b_s t_s}$$

The weighted minimum guaranteed compression yield strength for a panel was obtained from the preceding equation when the minimum guaranteed yield strengths of 64 and 57 ksi were substituted for $(F_{YP})_{st}$ and $(F_{YP})_s$, respectively. These minimum guaranteed yield strengths were supplied by the Consolidated Vultee Aircraft Corporation.

The average stress at maximum load that is obtained from steps (4) and (5) is the average stress, adjusted to minimum guaranteed material properties, for a panel with equal numbers of stiffeners and bays.

(6) The coefficient of end fixity for the specimens was determined by tests of the eight longest and narrowest specimens. The longest and narrowest specimens for the column tests were selected in order to minimize the effects of sheet buckling and deviation from the Euler curve. The average of the fixity coefficients for the eight panel columns was found to be 3.75, and this value was assumed to apply to all panels.

The lengths of the test panels were reduced to equivalent pin-ended column lengths by multiplying by $\sqrt{1/3.75}$. For these values of pin-ended column lengths, the adjusted average stresses at maximum load were plotted by using the upper abscissa scales in figures 5 to 12, parts (a). The lower abscissa scales, for $c = 1.5$, were obtained by multiplying values of length on the upper abscissa scales by $\sqrt{1.5/1}$.

(7) The dashed curves in figures 5 to 12, parts (a), were obtained from cross plots of the data as presented in parts (b). The test points in parts (b) are the same test points as in parts (a) but are plotted to show the strength of the panels for different values of the sheet thickness. For each stiffener section, the average of the values of σ_{st} for each value of $L/\sqrt{c}$ was obtained for the specimens with the smallest value of sheet thickness. These values of stress were plotted in parts (b) at zero sheet thickness for the given stiffener sections. These values are not shown as test points and were used only as a guide in fairing the curves for the test points.

(8) The critical stresses for the sheet were determined from the measured strains in the centers of the bays. For the panels on which strain measurements could be obtained on both sides of the sheet in a bay, the average strain at the middle of the bay was plotted against the average strain at the edge of the bay. The edge strain at which this curve deviated from a straight line was taken as the critical strain. The load on the panel at the critical strain was then obtained from a curve of load against strain in the stiffeners. For some hat-stiffened panels, the indication of critical strain was obtained from strain measurements on only one side of the sheet. For these panels, the load at which the strain on the crest of a buckle reached its maximum compressive value was selected as the critical load. The average stresses in the panels at the loads corresponding

to the critical strains are indicated in figures 5 to 12, parts (a), by short horizontal lines. These stresses are also plotted in figures 13 and 14 against the ratio of the width of sheet between adjacent rivet rows to the thickness of the sheet.

For the panels in which the average stress when sheet buckling occurred was greater than the proportional limit of the sheet material, the adjustments of the buckling stresses to minimum guaranteed yield strengths and to a panel with four stiffeners and four bays were made according to the method given in steps (4) and (5). In making these adjustments, the values of stress when sheet buckling occurred were used in place of the values of stress at maximum load.

REFERENCES

1. Levy, Samuel, and Krupen, Philip: Large-Deflection Theory for End Compression of Long Rectangular Plates Rigidly Clamped along Two Edges. NACA TN No. 884, 1943.

2. Anon: Strength of Aircraft Elements. ANC-5, Army-Navy-Civil Committee on Aircraft Design Criteria. Revised ed., Dec. 1942.

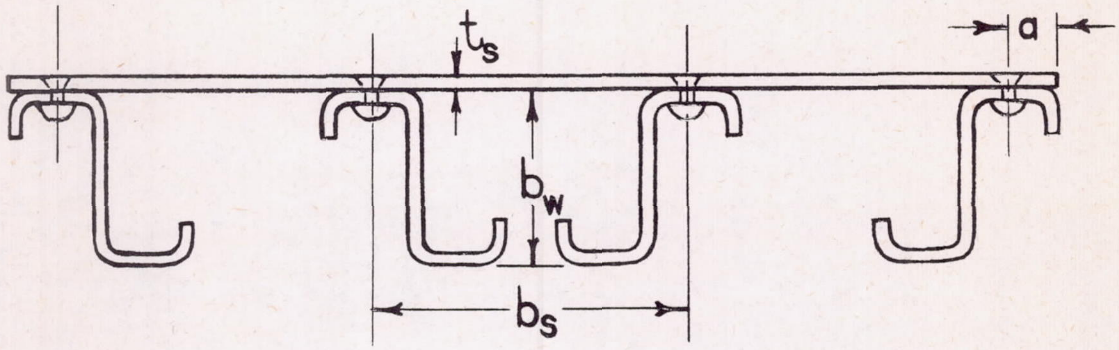

Figure 1.- Typical cross section of panel with Z-section stiffeners.

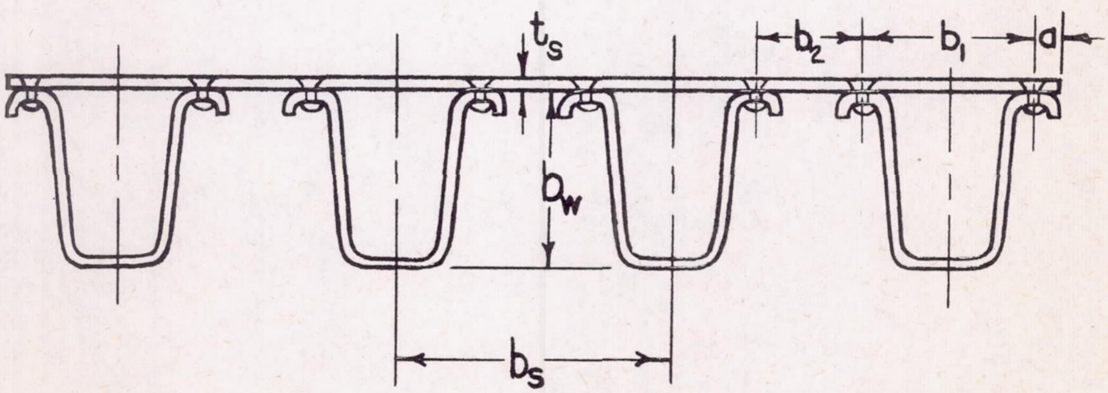

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Figure 2.- Typical cross section of panel with hat-section stiffeners.

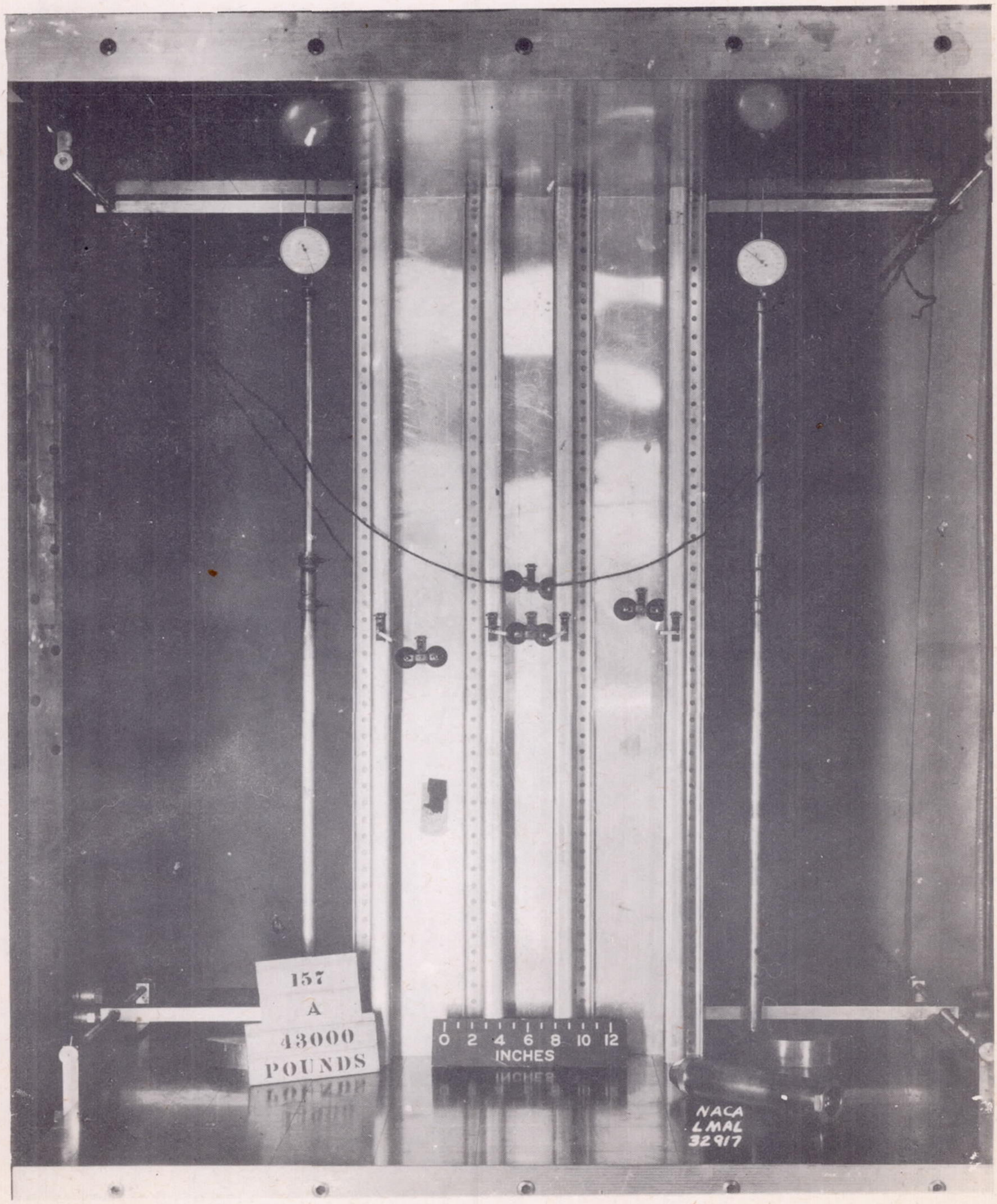


Figure 3.- Specimen with Z-section stiffeners under test.

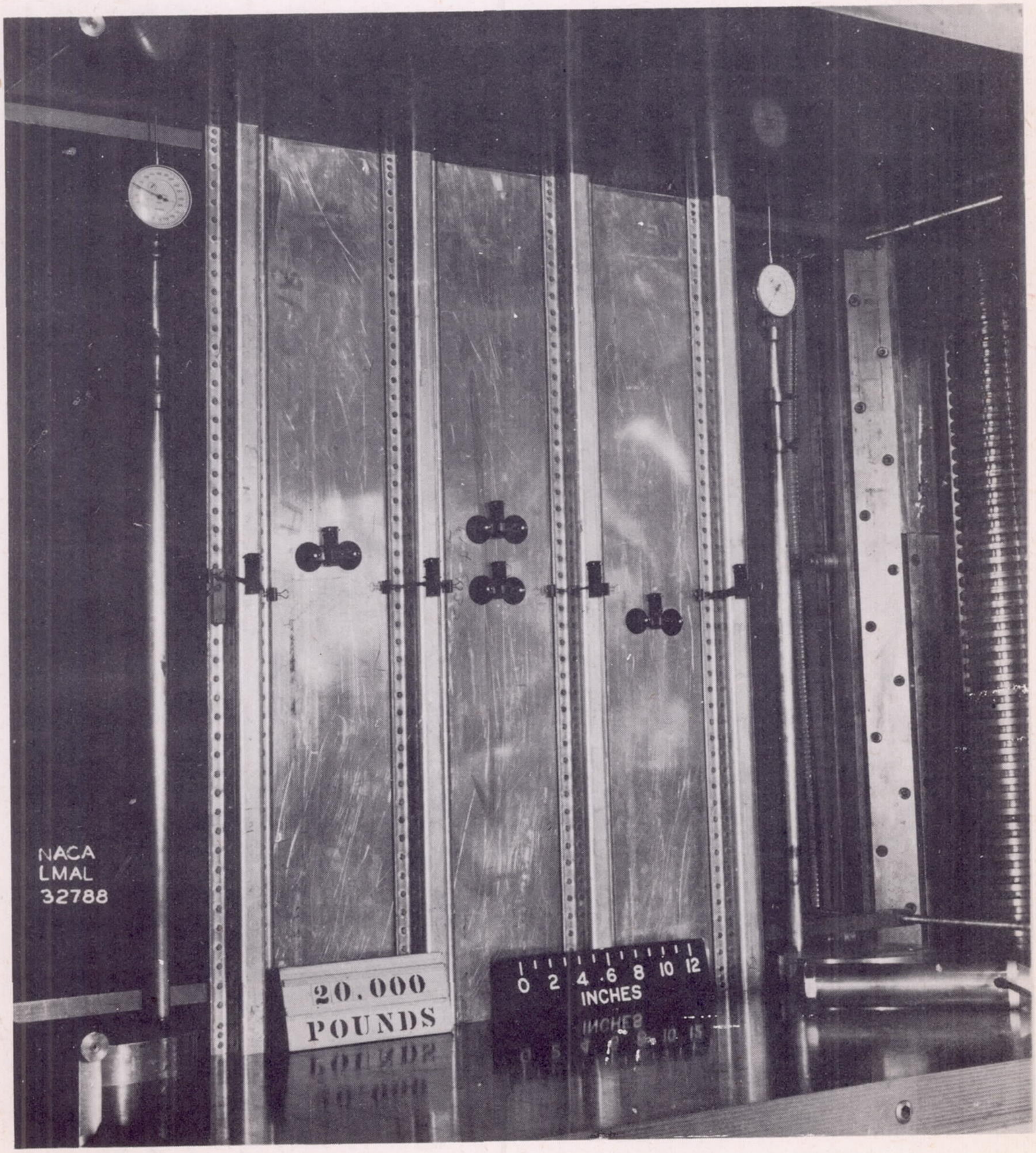
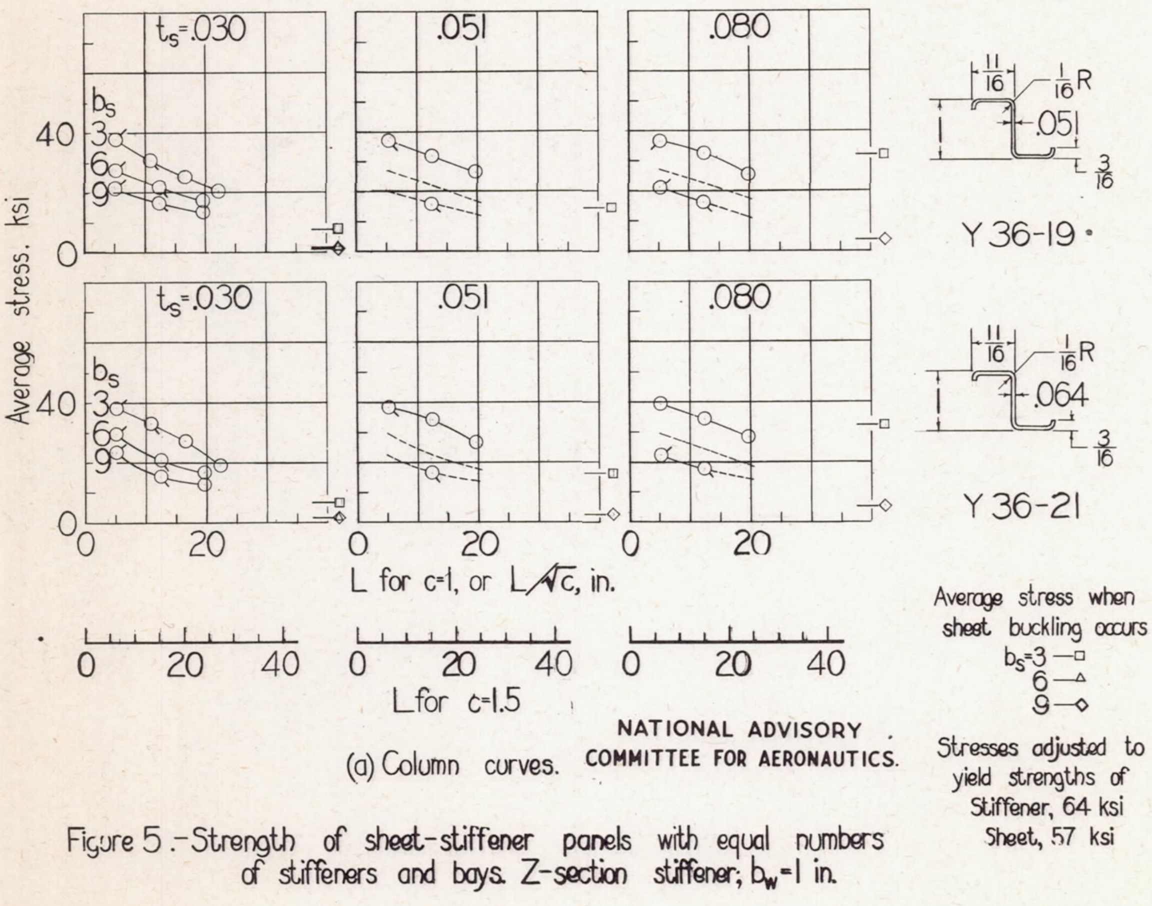


Figure 4.- Specimen with hat-section stiffeners under test.



(a) Column curves.

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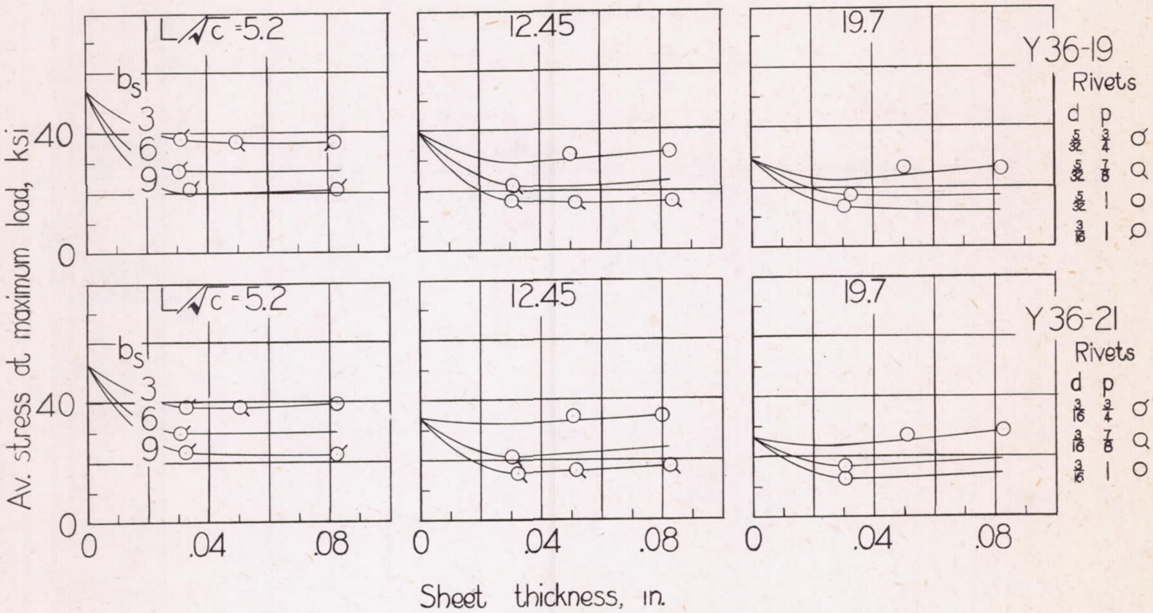
Figure 5.- Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Z-section stiffener; b_w=1 in.



(b) Stress plotted against sheet thickness for different column lengths.

Figure 5.-Concluded.

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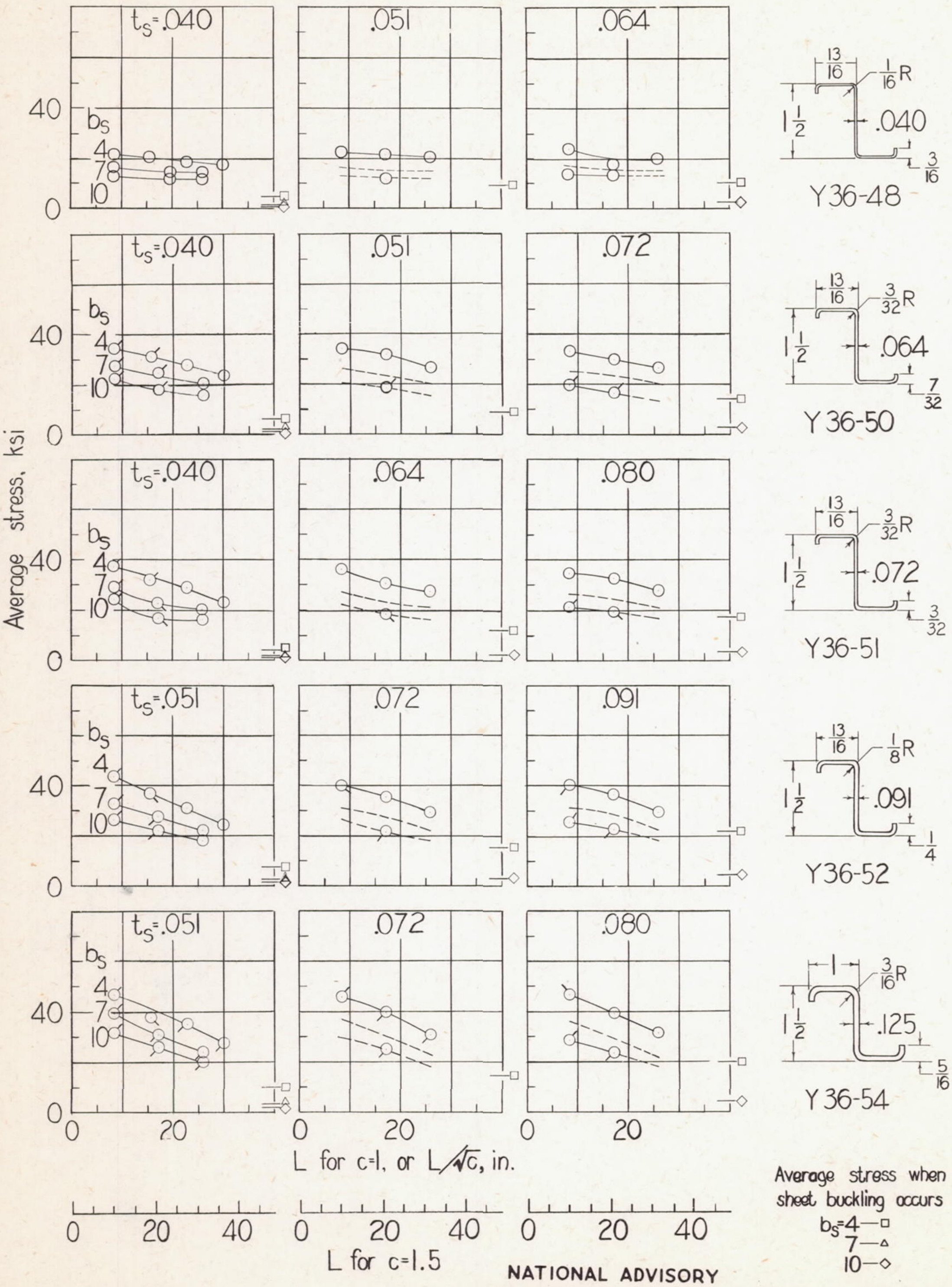

(a) Column curves.

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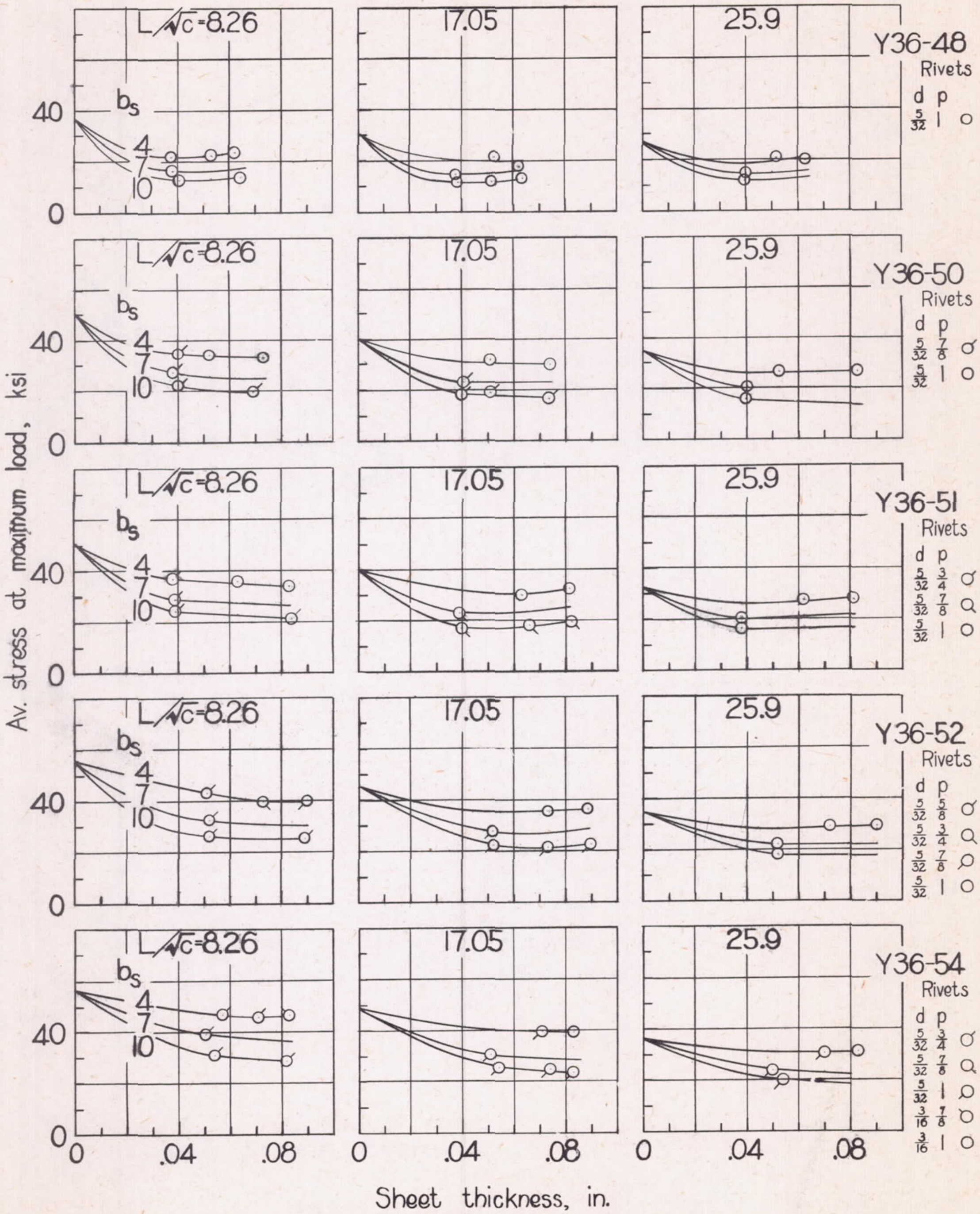
Figure 6 .- Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Z-section stiffener; $b_W = 1\frac{1}{2}$ in.



(b) Stress plotted against sheet thickness for different column lengths.

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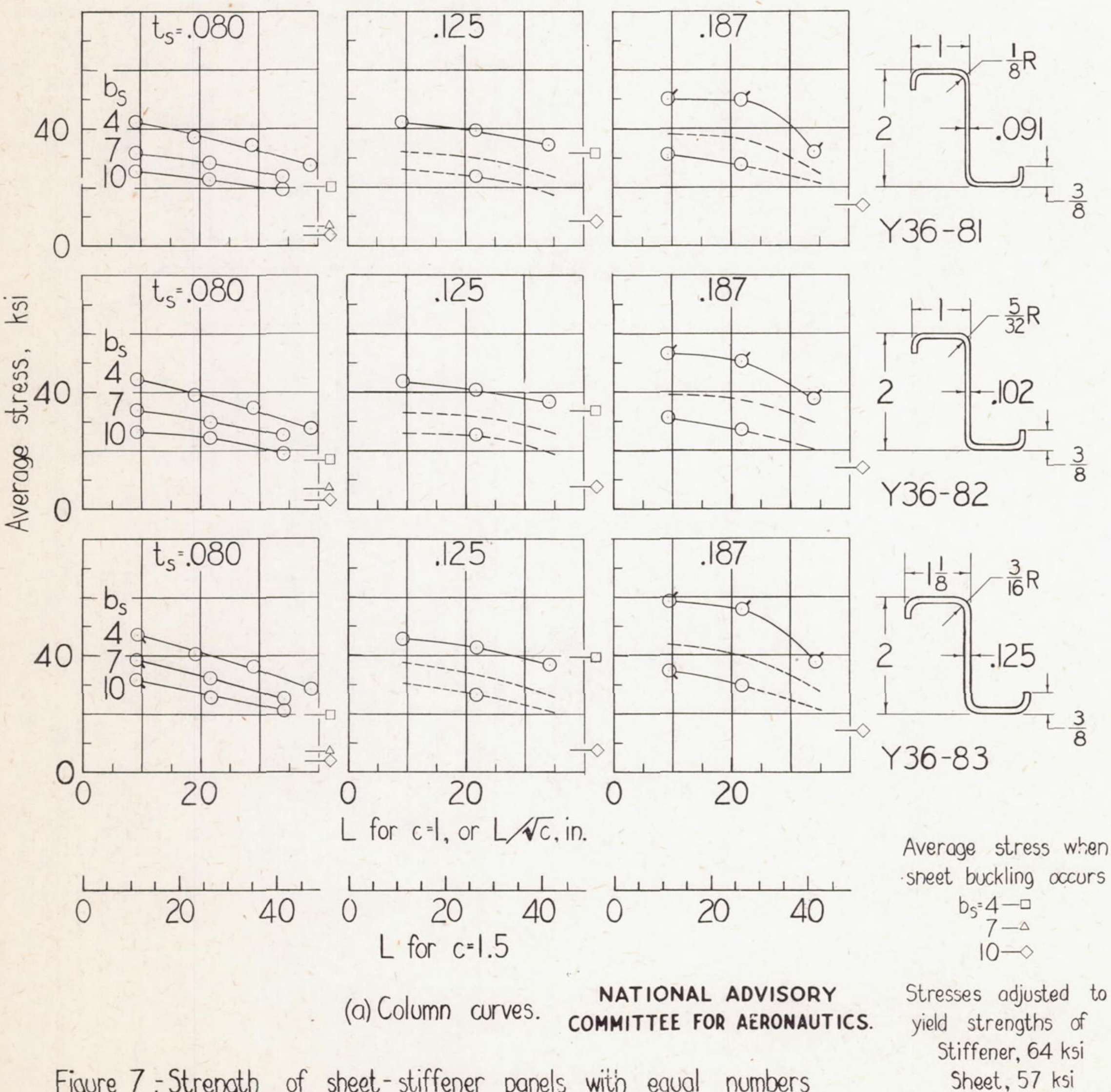
Figure 6.- Concluded.



(a) Column curves.

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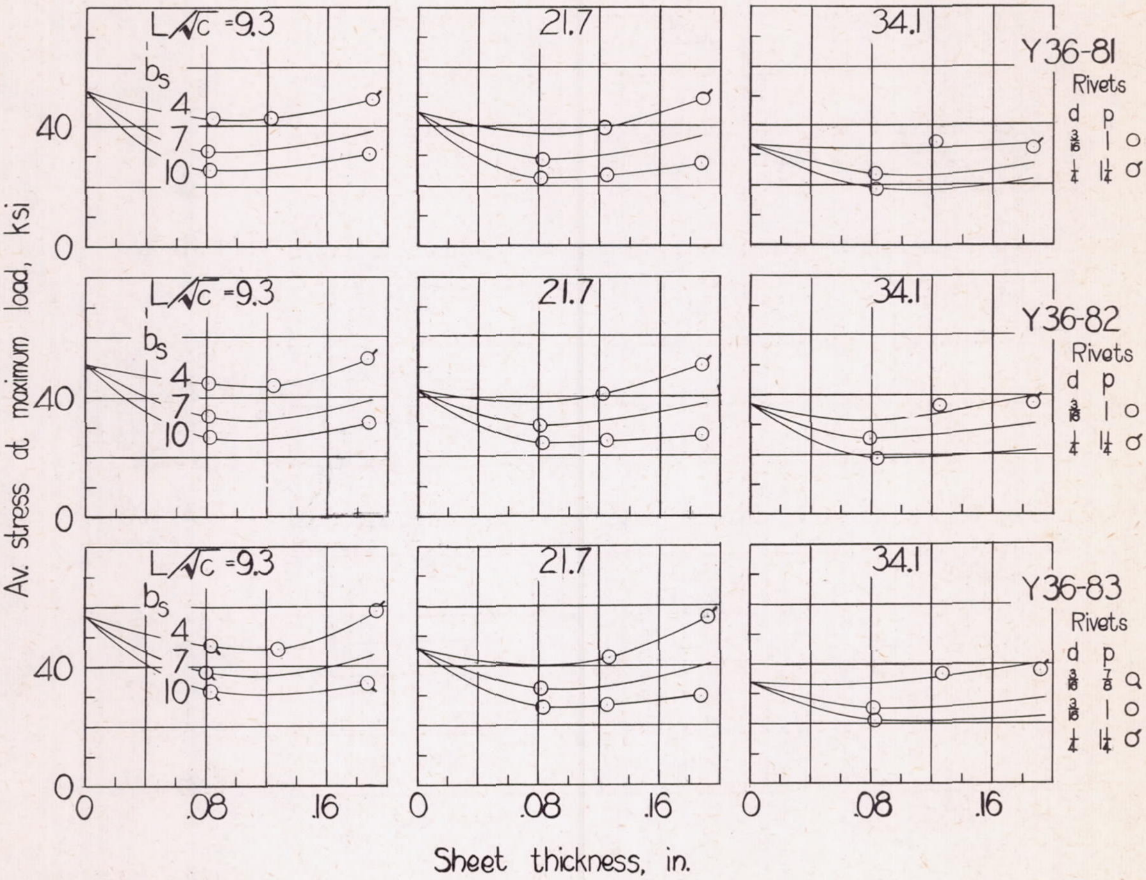
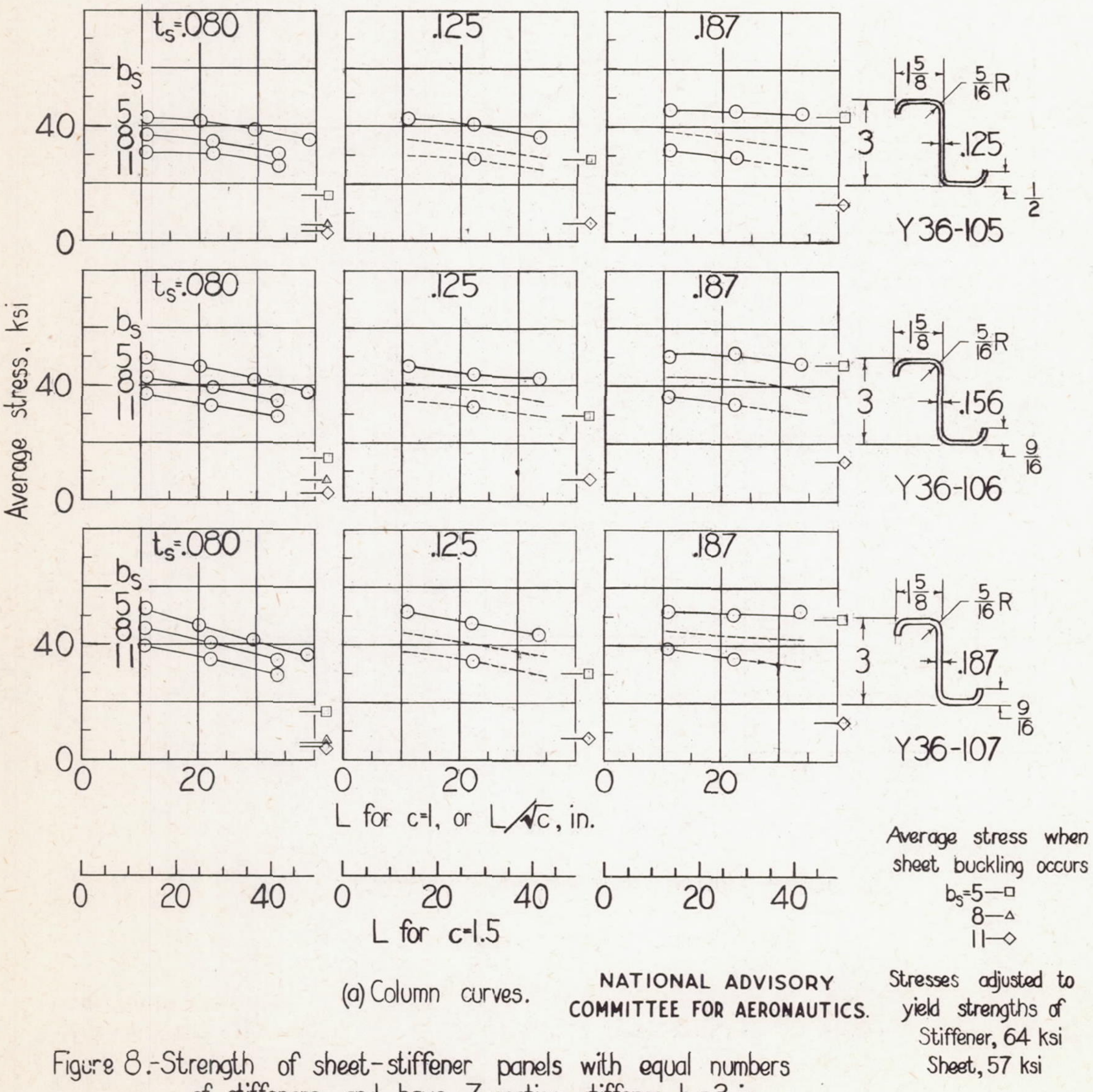
Figure 7.- Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Z-section stiffener; b_w=2 in.



(b) Stress plotted against sheet thickness for different column lengths.

Figure 7.- Concluded.



(a) Column curves.

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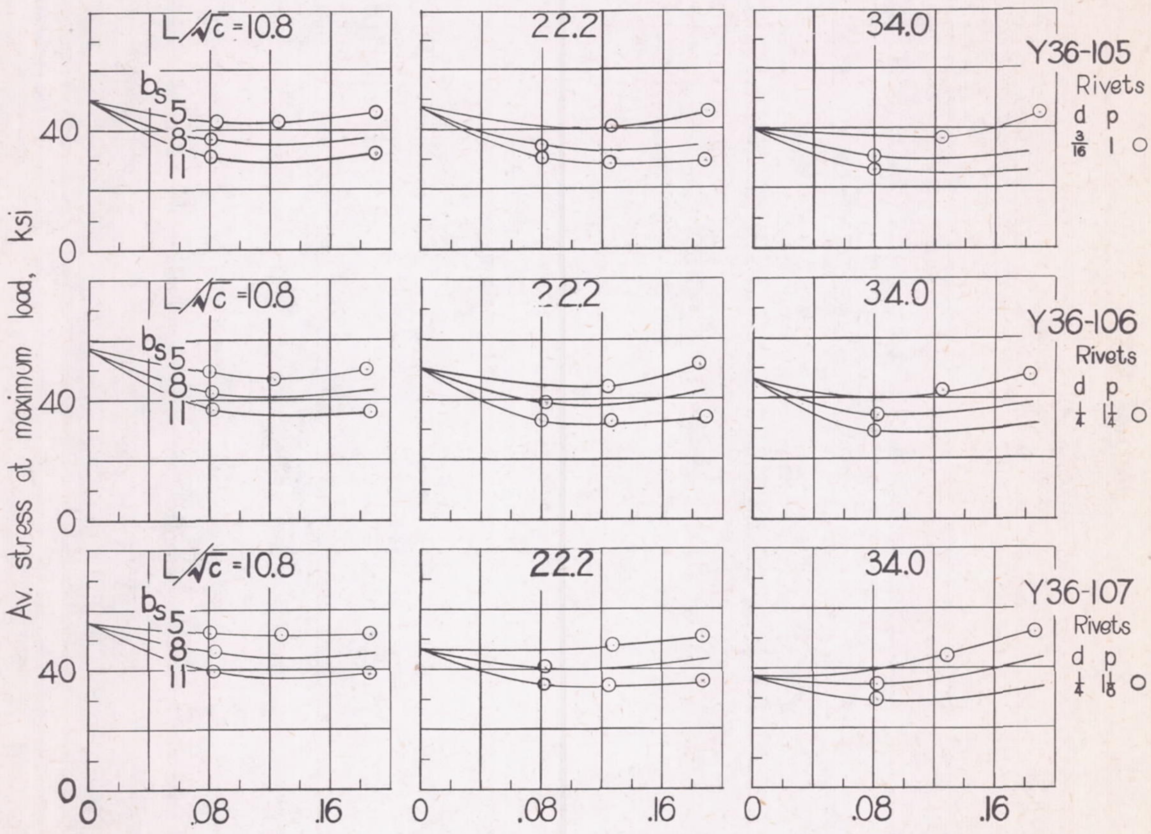
Figure 8.-Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Z-section stiffener; b_W=3 in.



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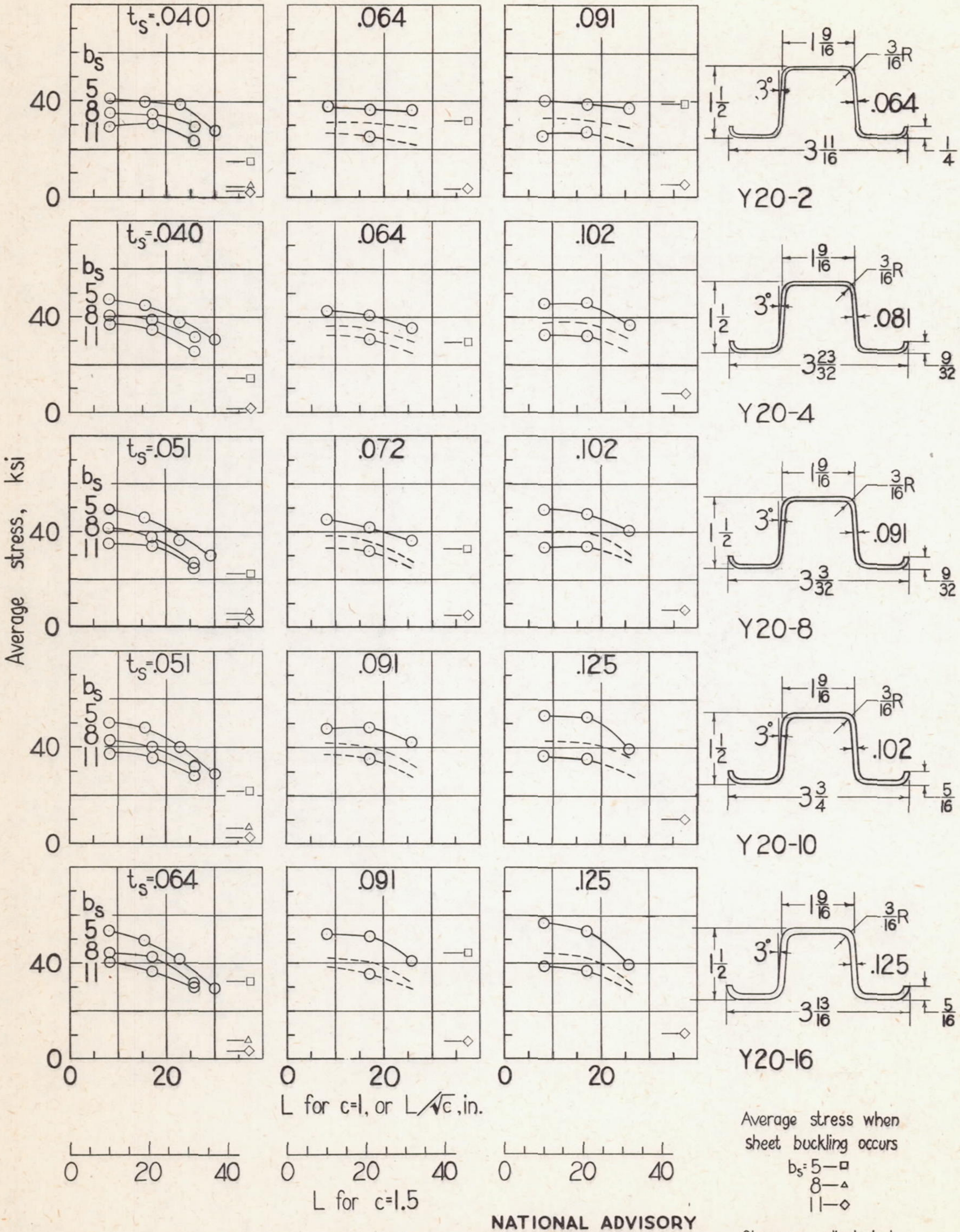
(b) Stress plotted against sheet thickness for different column lengths.

Figure 8.-Concluded.



(a) Column curves.

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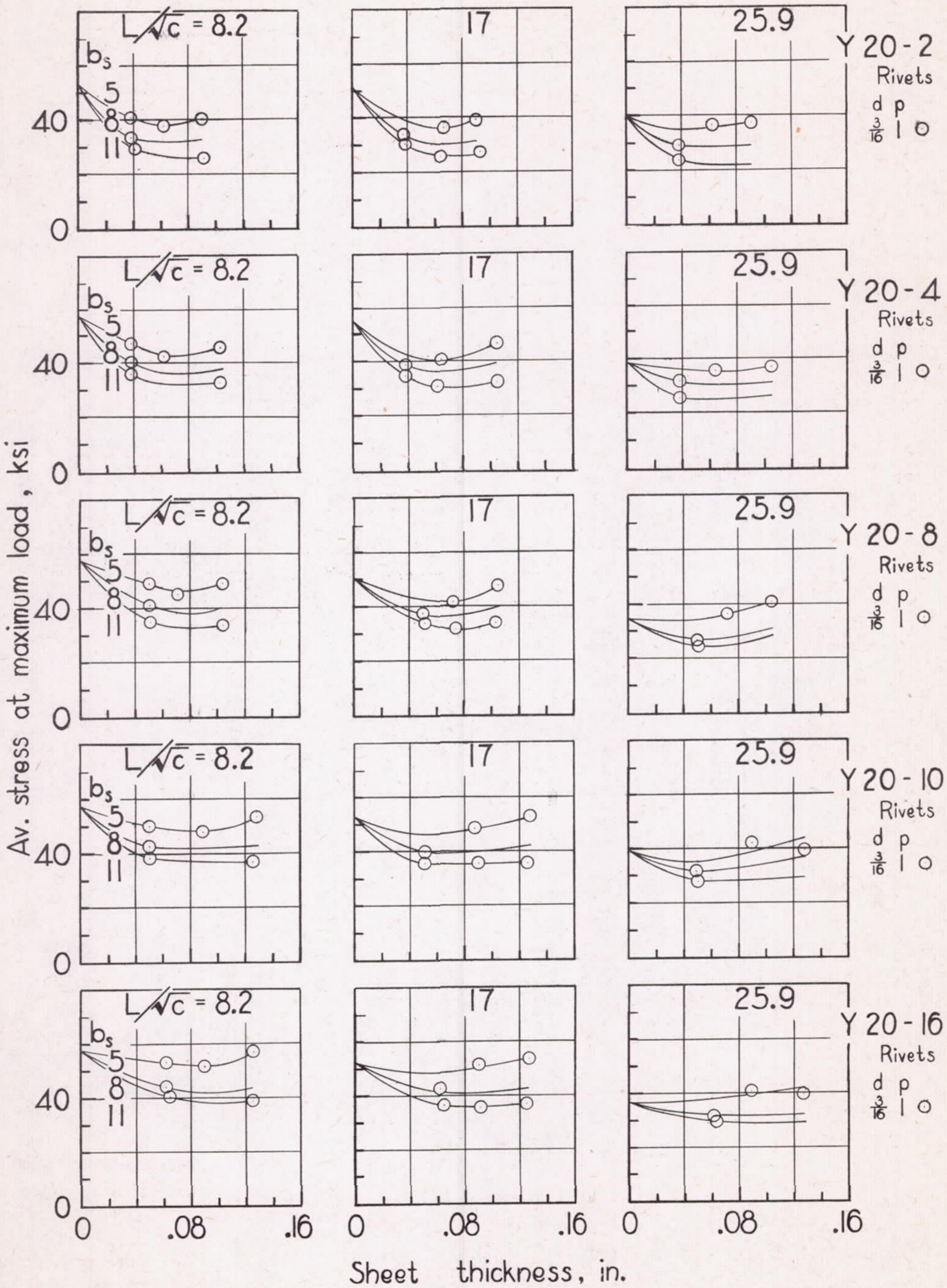
Figure 9.-Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Hat-section stiffener; b_W=$1\frac{1}{2}$ in.



(b) Stress plotted against sheet thickness for different column lengths.

Figure 9. -Concluded.

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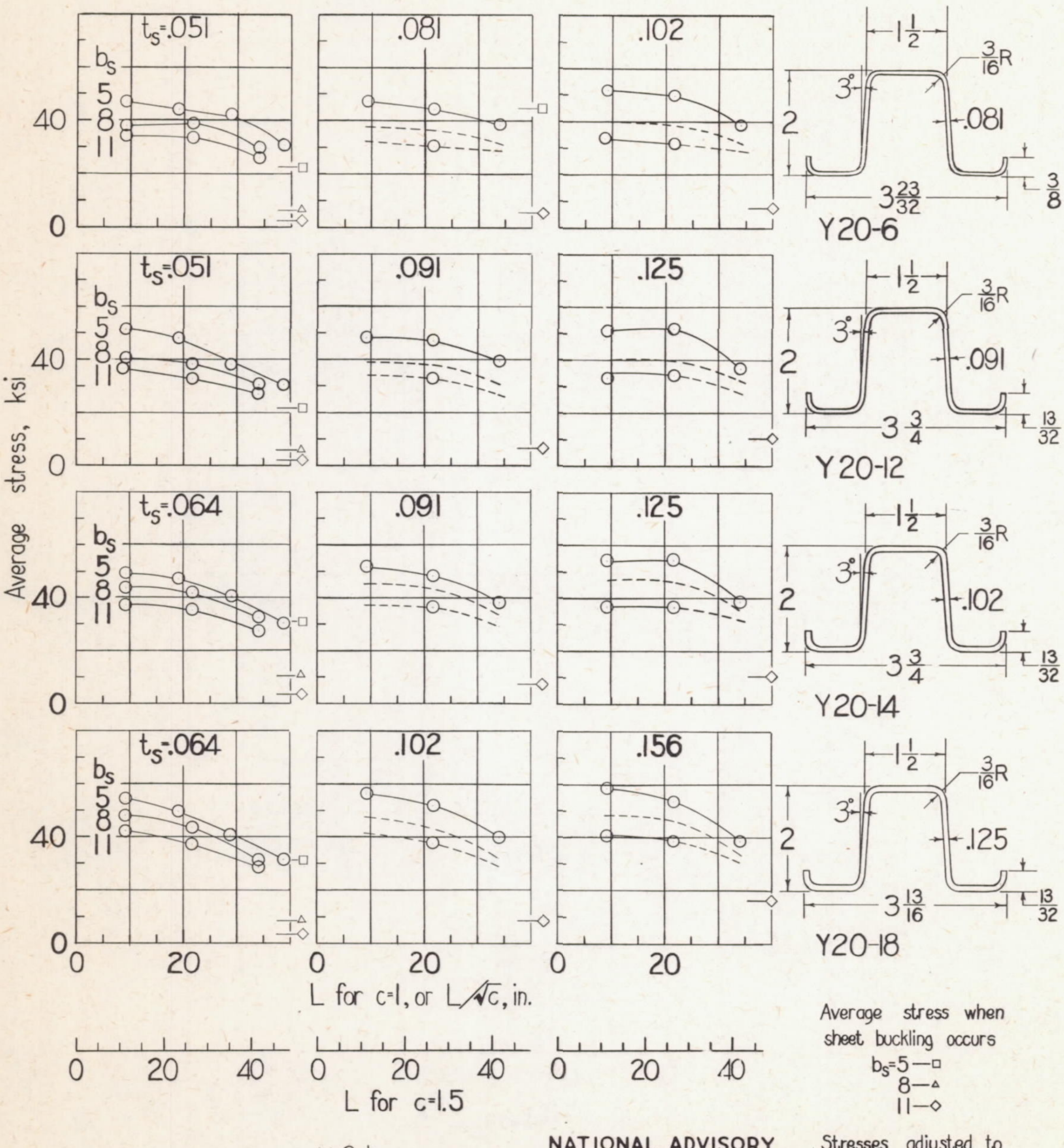

Average stress when sheet buckling occurs
b_s=5 —□
8—△
11—◇

Stresses adjusted to yield strengths of
Stiffener, 64 ksi
Sheet, 57 ksi

(a) Column curves.

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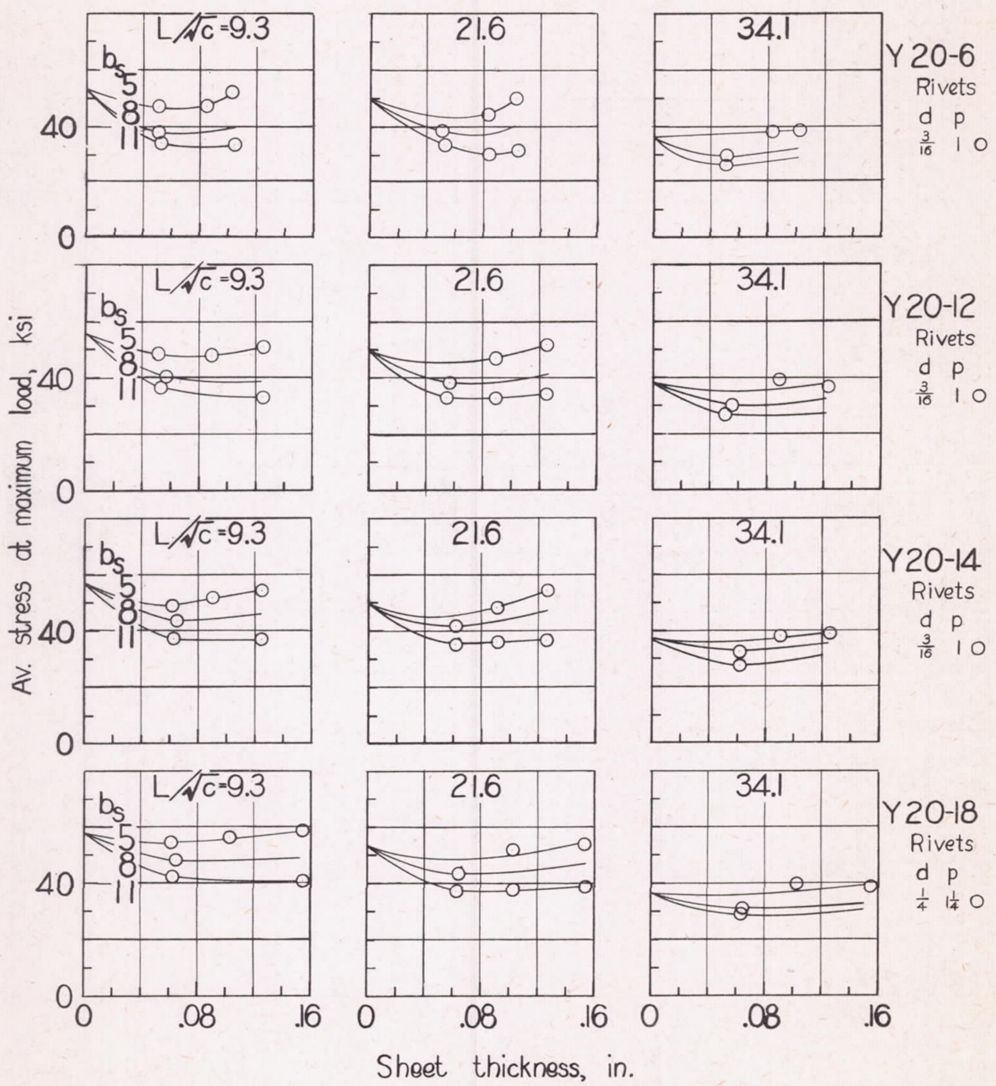
Figure 10.- Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Hat-section stiffener; b_w=2 in.



(b) Stress plotted against sheet thickness for different column lengths.

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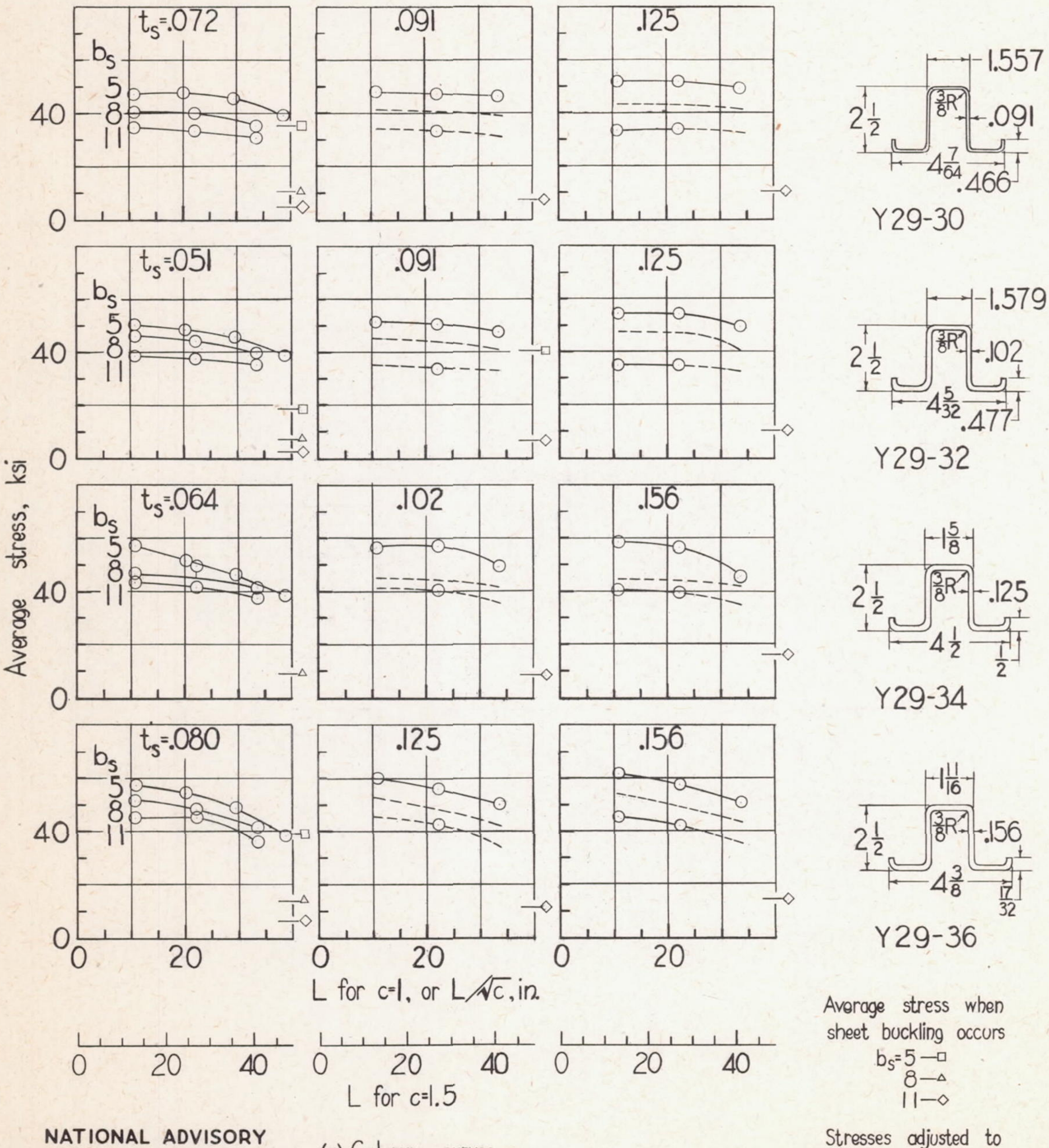
Figure 10.- Concluded.



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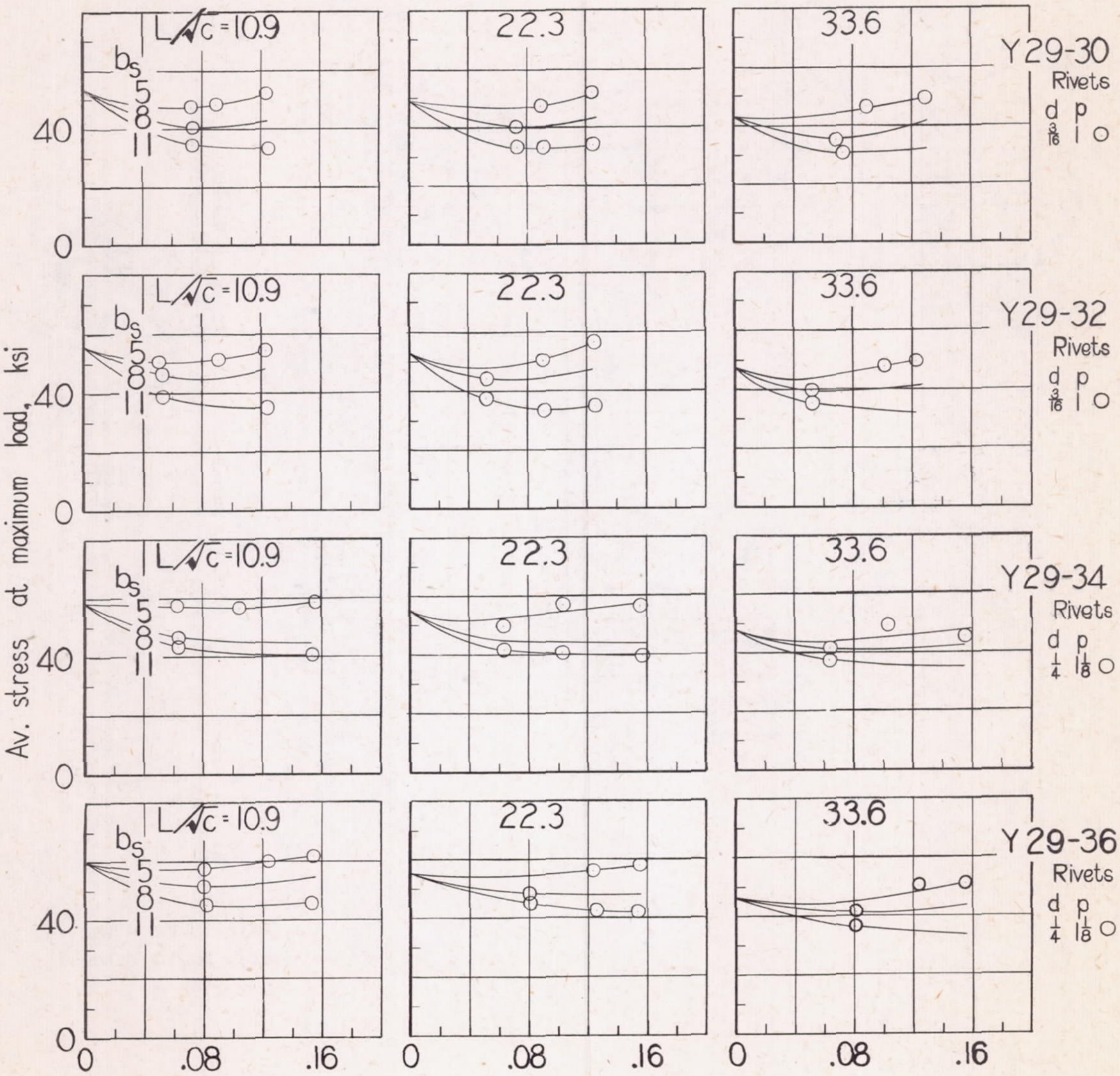
(a) Column curves.

Figure 11.- Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Hat-section stiffener; $b_w = 2\frac{1}{2}$ in.



(b) Stress plotted against sheet thickness for different column lengths.

Figure 11.-Concluded.

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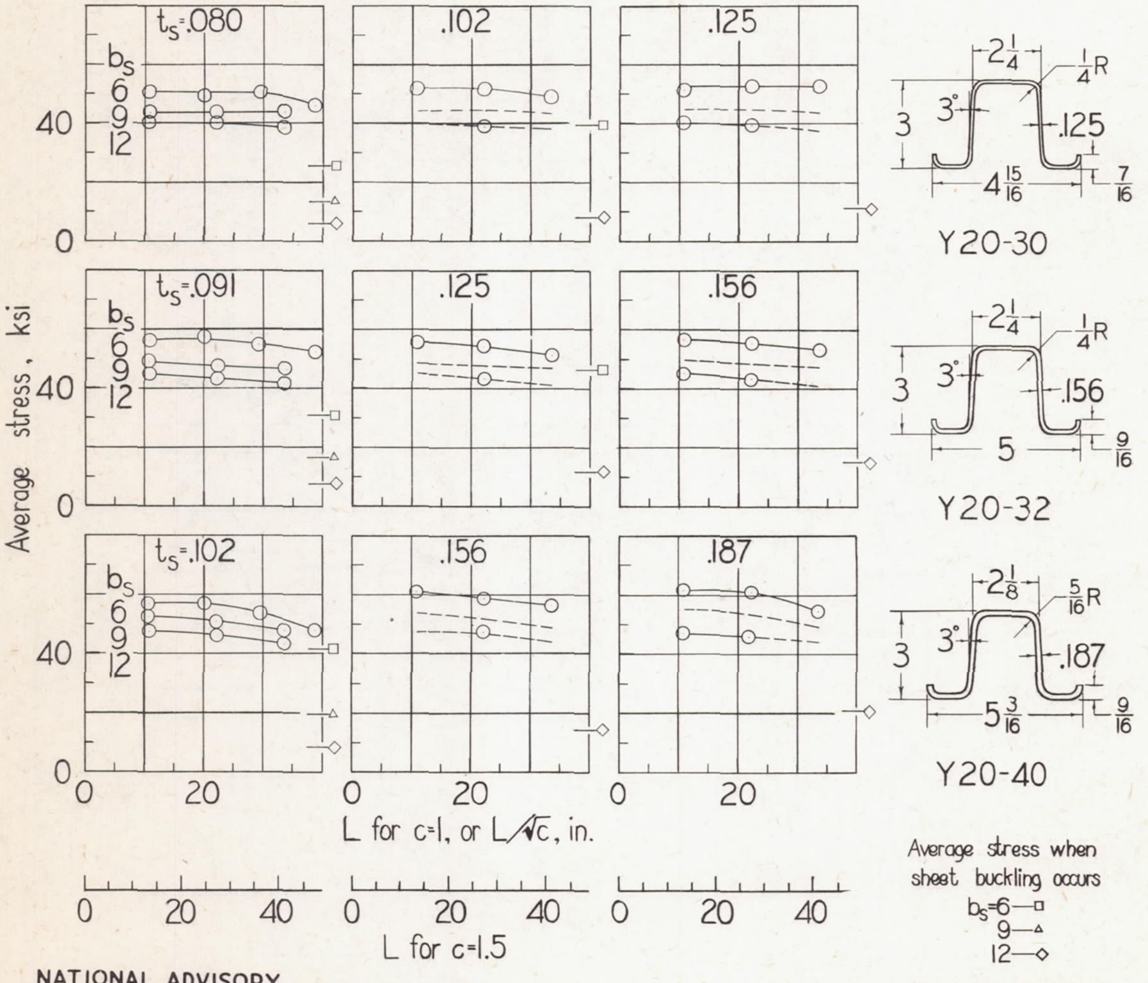

Average stress when sheet buckling occurs
b_s=6 —□
9 —△
12 —◇

Stresses adjusted to yield strengths of Stiffener, 64 ksi Sheet, 57 ksi

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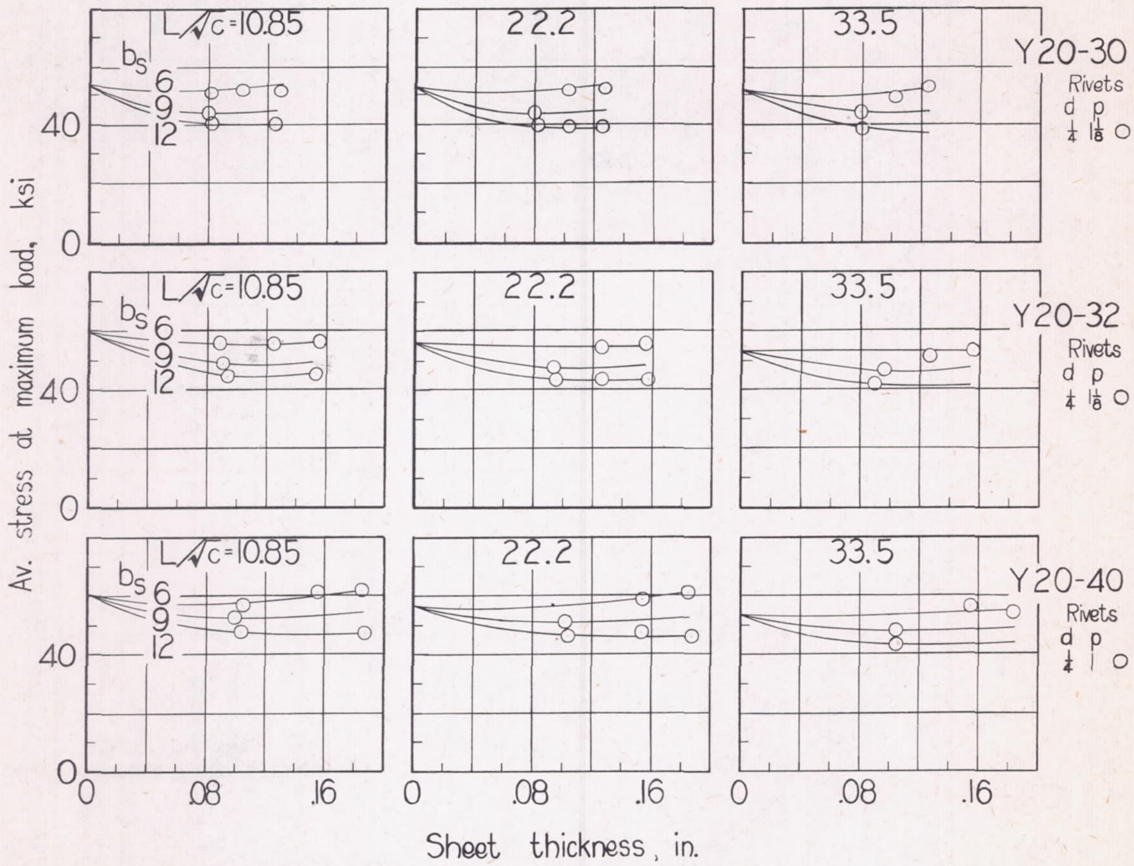
(a) Column curves.

Figure 12.- Strength of sheet-stiffener panels with equal numbers of stiffeners and bays. Hat-section stiffener; b_W=3 in.



(b) Stress plotted against sheet thickness for different column lengths.

Figure 12.-Concluded.

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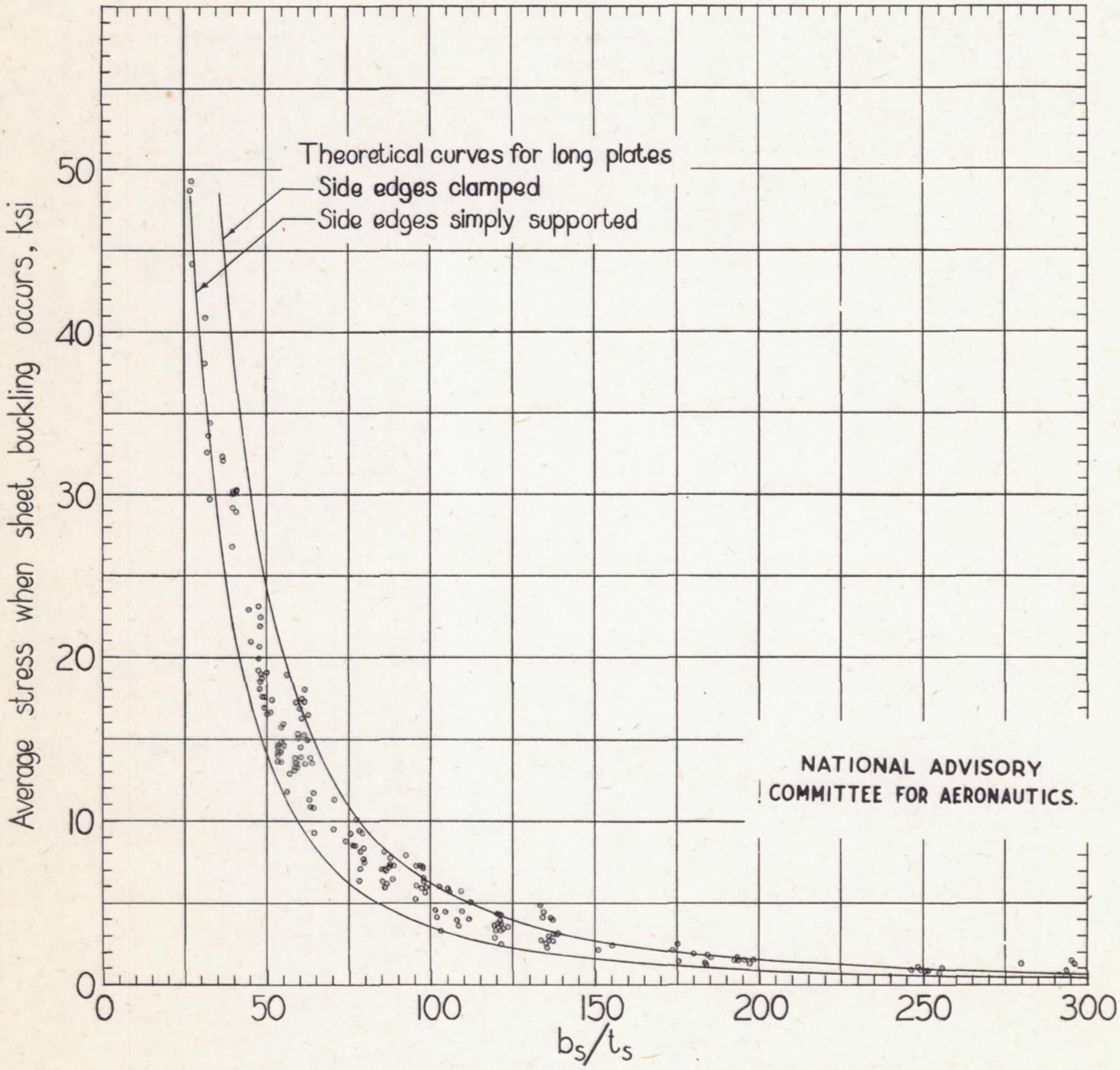

Figure 13.- Average stress when sheet buckling occurs for panels with Z-section stiffeners.

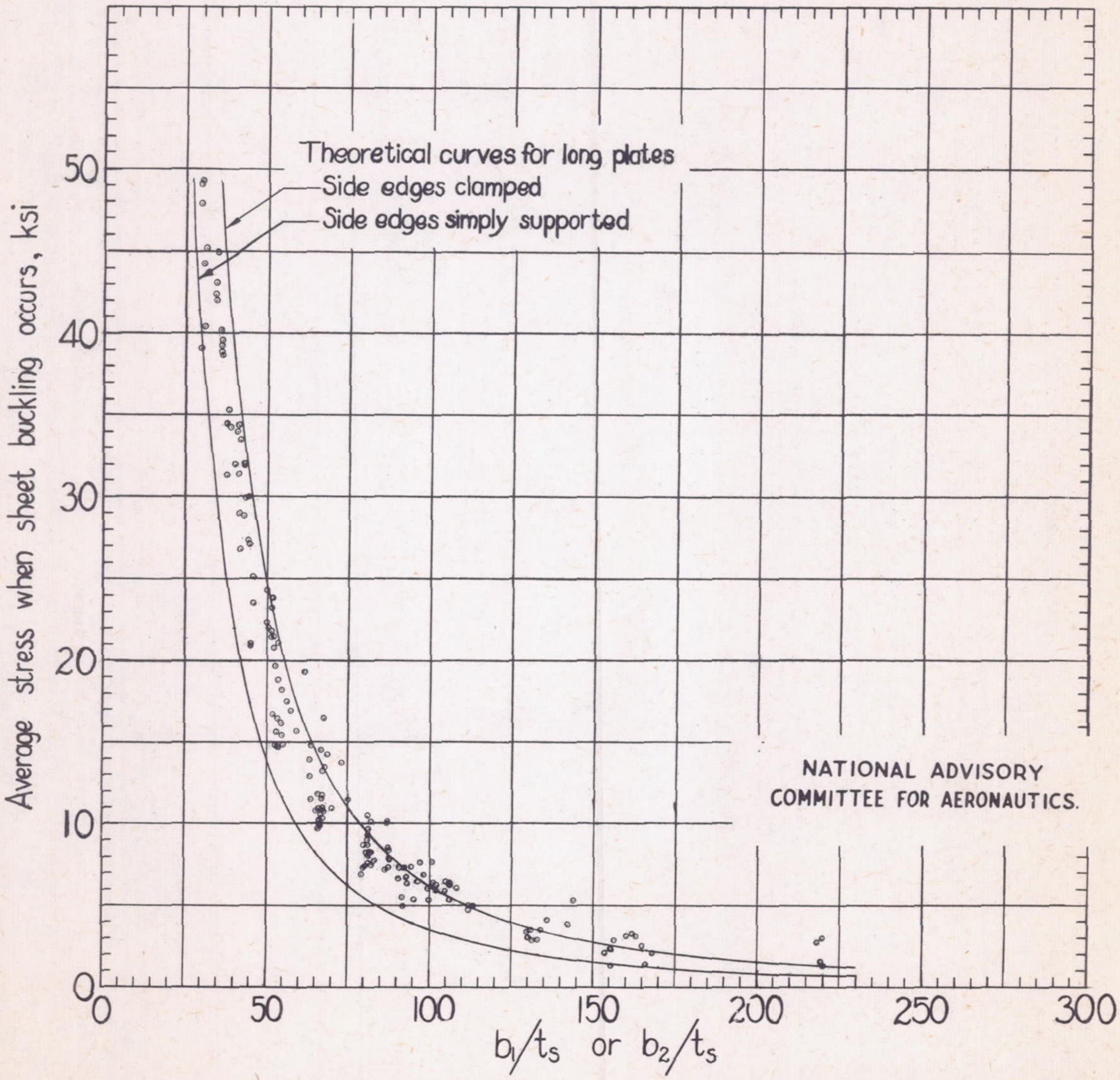

Figure 14.- Average stress when sheet buckling occurs for panels with hat-section stiffeners.